Preliminary Shock Wave Studies in Alumina and Tungsten Carbide

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Preliminary Shock Wave Studies In Alumina And Tungsten Carbide

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ABSTRACT

The present report describes the results of shock wave investigations conducted to determine shear strengths of two materials: an alumina (Al_2O_3), commercially produced by Coors as AD995, and pressure assisted densified tungsten carbide (WC) manufactured by Cercom. In addition, an effort was made to recover shock compressed AD995 in order to determine the change in the initial microstructure of AD995 due to shock and release wave propagation. The shear strength of these materials was obtained from the measurements of longitudinal and lateral stress under a given compression. Shock Hugoniot of AD995 and WC reported in earlier investigations provided the longitudinal stresses necessary to obtain the values of shear strengths. These when used in conjunction with the lateral stress measured by means of a manganin gage in the current investigation yield the values of shear strength for these materials.

INTRODUCTION

Ceramics are increasingly used as one critical component of protective systems. The importance of ceramics in these systems stems from such attractive properties as low density, low volume compressibility, and high shear strength. However, the shear strengths of some ceramics begin to degrade above an impact induced stress threshold. Thus, determination of shear strength under impact loading condition is critical for its potential use in a given protective system. The results of earlier shock wave compression studies of AD995 [1] and WC [2] indicated that (i) AD995 retains the shear strength to 12 GPa, and then begins to decline when shocked beyond 12 GPa and above 30 GPa AD995 has a vanishingly small shear strength; (ii) WC retained increasingly higher shear strength value with an increase in impact stress to 80 GPa. The values of shear strengths in the earlier studies were obtained from the shock Hugoniots and hydrodynamic equations of state of these respective materials. Earlier studies of Bourne and his coworkers [3-5] dealing with the shear strength of ceramics,

obtained from the measurements of longitudinal and lateral stress measurements on several ceramics, suggested that the shear strengths of ceramics near the impact surface of ceramics begin to decline due to propagation of a failure front with a decelerating velocity which comes to a stop over a short distance in the ceramic. Therefore, it was of interest to determine: (i) whether the shear strength of these two ceramics as a function of impact stress follow the trend reported in earlier studies, and (ii) whether the shear strengths of these materials near the impact surfaces decline due to failure front propagation. This report describes the results of lateral stress measurements obtained from six experiments conducted in AD995 and four experiments conducted in WC.

MATERIALS

AD995 is composed of polycrystalline alumina and aluminosilicate glass. This material is 99.5% alumina with a density of 3.880 ± 0.003 Mg/m^3. Theoretical density of polycrystalline alumina should be 3.96 Mg/m^3. The deficit in the density of AD995 is attributed to the presence of the aluminosilicate glassy phase and pores in the material. Ultrasonic longitudinal and shear waves in the material are measured to propagate with 10.56 ± 0.03, and 6.25 ± 0.08 km/s, respectively.

Cercom WC is a composite consisting of two distinct materials, namely, WC (97.2% by weight) and W_2C (2.8% by weight)[6]. W_2C is a byproduct of the densification process. WC and W_2C both crystallize in hexagonal form. The theoretical densities of these carbides are 15.7 and 17.2 Mg/m^3, respectively [7]. Both melt around 3050 K and have similar thermal expansion coefficients. The only other property of W_2C reported is the value of longitudinal elastic wave velocity, which is 4.94 km/s [7]. The measured values of density, elastic longitudinal and shear wave velocities of this tungsten carbide composite are 15.545 ±0.002 Mg/m^3, 7.04 ± 0.005 km/s, and 4.31± 0.002 km/s, respectively. The values of density and elastic wave velocities for Cercom WC measured at The US Army Research Laboratory (ARL) and Sandia National Laboratory (SNL) are within the errors of measurements. Since the measured value of the density of Cercom WC is less than the reported densities of WC and W_2C, it must contain some lighter impurities with or without porosity. We have no information about these impurities but the void volume fraction is estimated to be around 0.01 [6].

DESIGN OF EXPERIMENT

The impact experiments were conducted using a 50 mm diameter gas gun. Impact velocity was measured to an accuracy of 0.5% using a sequential pin-shorting method and tilt was fixed to be less than 1 mrad by means of an adjustable specimen mount. Impactor plates were made from lapped copper, aluminium, and PMMA discs and were mounted onto a polycarbonate sabot with a relieved front surface in order that the rear of the flyer plate remained unconfined. Targets were flat to less than 2 μm across the surface. Lateral stresses were measured using manganin stress gauges of type J2M-SS-580SF- 025 (resistance 25 W).

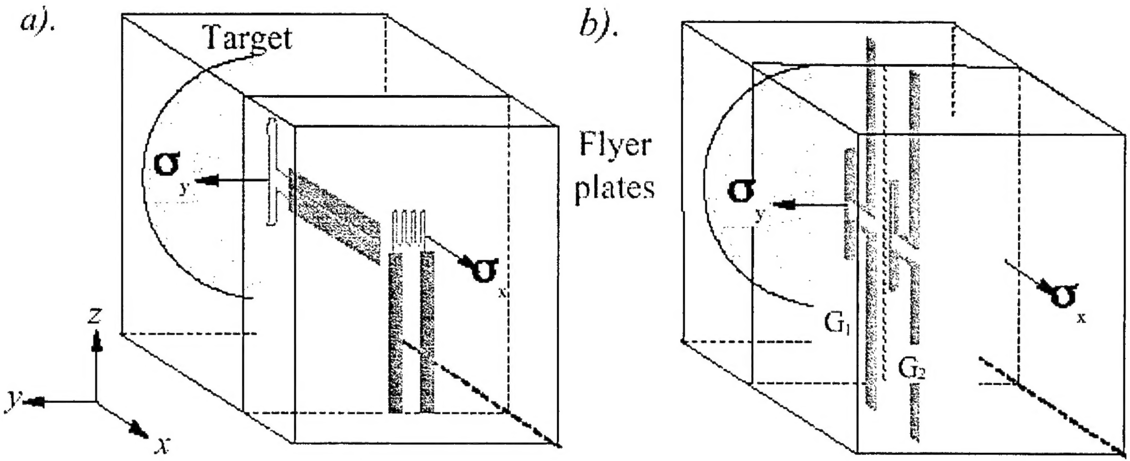

Figure 1. Experimental arrangement for lateral and longitudinal stress experiments. a) Longitudinal and lateral stress gauge b). Multiple lateral gauge measurements.

The gauges were placed at either 2 mm or at 2 and 6 mm distances from the impact face as shown in Figure 1. They had an active width of 240 μm. The longitudinal stresses for generated in these experiments were calculated from the published Hugoniots of AD995 [1] and WC [2].

RESULTS

AD995

Hugoniot of AD995

The Hugoniot Elastic Limit (HEL) of AD995 is found to be 6.67 ± 0.24 GPa. Grady [8] reports a value of 6.5 GPa for the HEL of this material, which is in good agreement with our

value. The associated values of density and particle velocity are 3.940 ± 0.004 Mg/m^3 and 0.162 ± 0.005 km/s, respectively.

The results obtained in these two works indicate that the deformation of AD995 above its HEL is elastic-plastic to around 12 GPa. Above 12 GPa, AD995 begins to show a decreasing magnitude of shear strength with an increase in shock stress. AD995 suffers a total loss of shear strength around 31 GPa. Mashimo et al [9] have also observed similar trends in the shear strength of alumina.

Shear Strength of AD995 from Lateral Stress Measurements

Six experiments were performed to measure shear strength of AD995 to a maximum impact stress of magnitude 19 GPa. The results of these experiments are given in Table 1.

Table 1. Results of AD995 experiments.

Experiment	Impactor	Impact		Mass	Lateral		Shear	
		Velocity (km/s)	Stresses (GPa)	Velocity (km/s)	σ_y (1) (GPa)	σ_y (1) (GPa)	τ (1) (GPa)	τ (2) (GPa)
1	Aluminum	0.590	6.51	0.159	0.99	1.62	2.76	2.44
2	Copper	0.467	8.55	0.243	2.10	3.97	3.22	2.29
3	Copper	0.550	10.16	0.287	3.21	4.87	3.48	2.64
4	Aluminum	0.402	4.50	0.109	0.56	1.64	1.97	1.43
5	Copper	0.962	18.55	0.511	10.75	11.57	3.90	3.49
6	Copper	0.547	10.14	0.286	3.02	5.22	3.56	2.46
6[1]	Copper	0.547	10.14	0.286	2.47[2]	3.20	3.84[2]	3.47

[1] Lateral gauge located 6 mm from the impact surface. [2] There appears to be a not fully developed discontinuity in Figure 3.

The lateral stress profiles in AD995 in these experiments are shown in Figure 2. These profiles were recorded at 2 mm from the impact surface in AD995 targets. These profiles show a two-step structure except at an impact stress of 18.5 GPa magnitude. This feature of lateral stress profile is similar to those observed by Bourne and his co-workers in other ceramics [3-5] and has been attributed to propagation of a failure front, which moves with a decreasing velocity as it propagates away from the impact surface of a ceramic. This suggestion of the front moving with decreasing velocity in the impacted ceramic is consistent

with the observation that when a lateral gage is placed at a depth of 6 mm from the impact surface, the recorded wave profile does not have a two-step structure. This may be easily seen from a plot of lateral stress profiles recorded in experiments 3 and 6 (Figure 3). The impact stresses generated in these experiments were 10.16 and 10.14 GPa, respectively. The results of these experiments also provide quantitative information about the replicability of

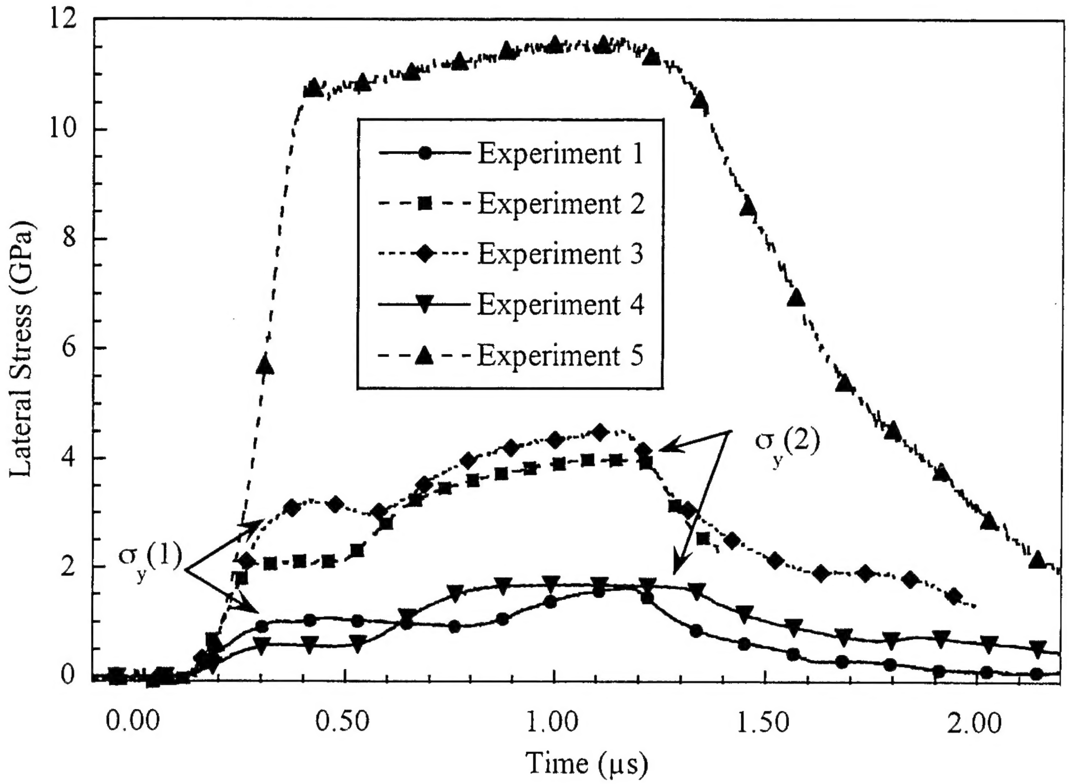

Figure 2. Lateral stress profiles at 2mm from the impact surface of AD995.

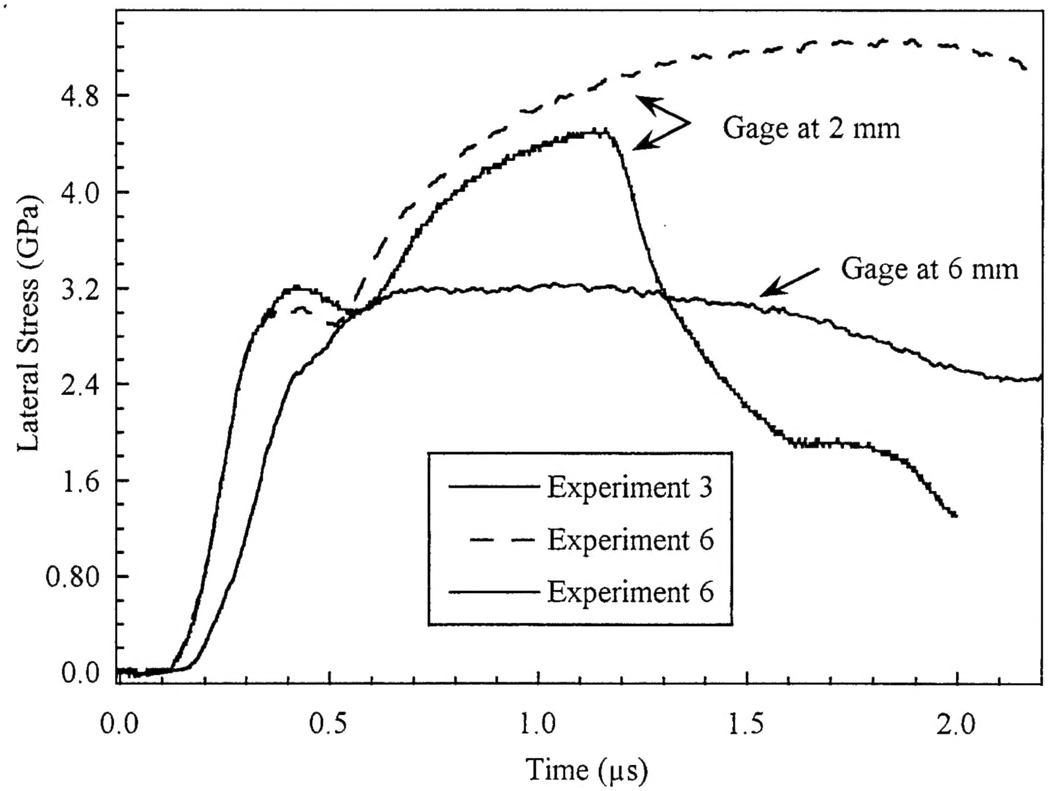

Figure 3. Lateral stress profiles in Experiments 3 and 6.

measured values of lateral stresses at a given impact stress. The initial magnitudes of lateral stress [σ_y (1)] followed by the second/higher magnitude of lateral stress [σ_y (2)] at a later time in the wave profile are given in Table 1. The ramp in a lateral stress profile makes it difficult to assign a representative value to σ_y (2). The reason for the existence of this observed ramp especially in experiments 2, 3, and 5 is not yet clear. The corresponding values of shear stresses are given as [τ(1)] and [τ(2)], respectively in this table. The values of shear stress are calculated from the relation

$$\tau = 0.5\ (\sigma_x - \sigma_y), \qquad (1)$$

where σ_x is the impact stress.

A plot of shear strength versus impact stress of AD995 is shown in Figure 4. In this figure the values of shear stresses (strength) calculated from the Hugoniot and equation of state of AD995 is represented by "Hydrodynamic". The values of shear strength calculated from

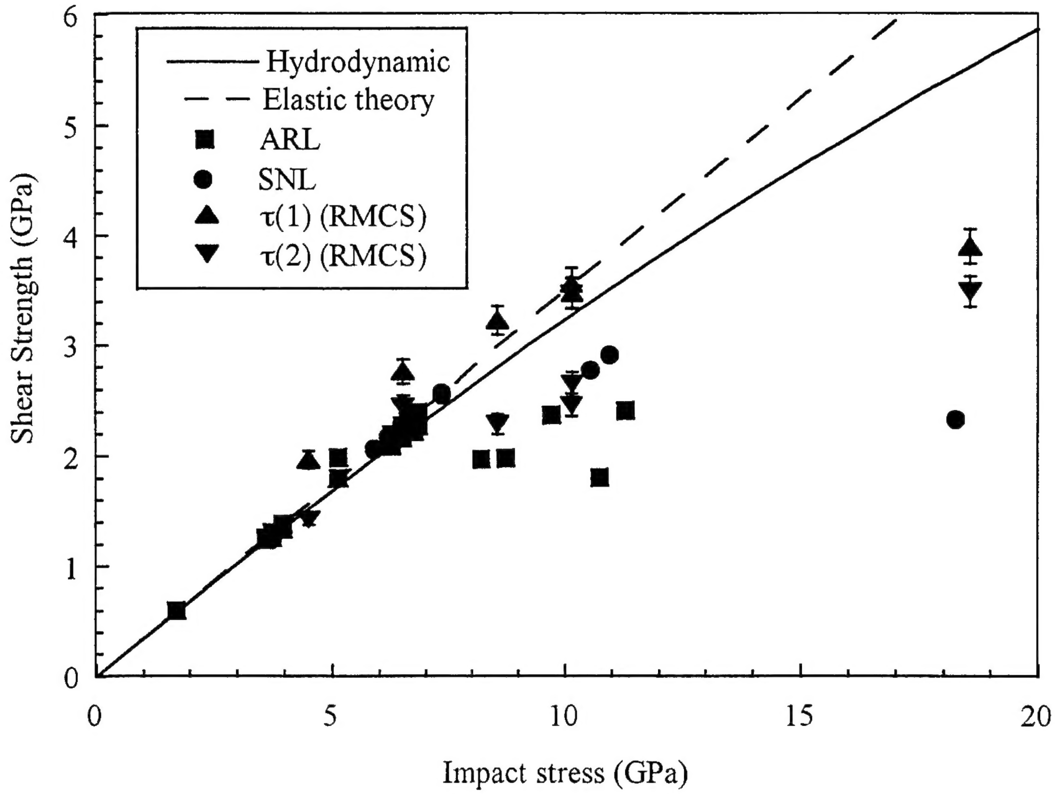

Figure 4. Shear stress versus impact stress in AD995.

linear elastic theory with the assumption that the Poisson's ratio remains unchanged at high pressures is represented by "Elastic theory". The values of shear strength for ARL and SNL experiments [1] are calculated from the Hugoniot of AD995 and the equation of state of AD995. There is no significant difference between the values of shear strength designated as "Elastic theory" and "Hydrodynamic" for impact stresses less than the HEL of AD995. This figure shows that the initial values of the shear strength i.e., $\tau(1)$ obtained from lateral stress profiles lies above elastic theory locus for impact stresses to 8.5 GPa. At impact stress of 10.2 GPa, the value of $\tau(1)$ lies on the Elastic theory locus. But the values of $\tau(2)$ lie on the elastic theory locus for the impact stress magnitude equal to or less than the HEL of AD995 i.e., 6.7 GPa. Above the HEL, $\tau(2)$ lie within the scatter of the values of shear strengths coordinates of ARL and SNL. However, the SNL shear strength value at an impact stress of 18 GPa is significantly smaller than the $\tau(2)$ obtained from the lateral stress measurement. Further, in experiment 6, the values of shear strength $\tau(2)$ obtained from the gages at 2 and 6 mm are 2.5 and 3.5 GPa, respectively. These are significantly different from one another and are perplexing. At present, the reasons for (i) the values of $\tau(1)$ lying above the Elastic theory locus to 8.5 GPa, (ii) a difference of 1 GPa in the value of final shear strength $\tau(2)$ in

experiment 6, and (iii) the discrepancy between the value of $\tau(2)$ and those for SNL at 18 GPa remains shrouded in mystery. But the measurements of lateral stresses appear to indicate that AD995 deforms like an elastic solid to 6.6 GPa, the HEL of AD995 determined in the earlier investigations.

Hugoniot of WC

The results of earlier shock wave study on WC [2] show that the Hugoniot Elastic Limit (HEL) of this material is 6.6 ± 0.5 GPa. This value of the HEL may not adequately represent the dynamic yield strength of the material because of the substantial post-yield hardening characteristics of this material shown by the pronounced slope of the precursor wave preceding the following final-state shock wave. The values of shock velocities following the elastic precursor are larger than the bulk sound wave velocity in Cercom WC at the ambient condition, i.e., 4.96-4.98 km/s. This suggests that the inelastic deformation above the HEL proceeds plastically in this material. The value of shear stress sustained by Cercom WC at the HEL obtained from the Hugoniot data and the hydrodynamic compression curve is 2.4 GPa. This compares well with the elastic value of shear stress, i.e., 2.5 ± 0.2 GPa.

Table 2. Results of WC experiments.

Experiment	Impactor	Impact		Mass	Lateral		Shear	
		Velocity (km/s)	Stresses (GPa)	Velocity (km/s)	σ_y (1) (GPa)	σ_y (1) (GPa)	$\tau(1)$ (GPa)	$\tau(2)$ (GPa)
1	PMMA	0.510	1.95	0.0178	0.094	0.219	0.93	0.86
2	Aluminum	0.347	4.68	0.043	0.262	1.944	2.21	1.36
3	Copper	0.320	8.70	0.0925	0.508	3.95	4.09	2.37
4	Copper	0.473	13.22	0.139	1.15	5.5-7.2	6.04	3.86-3.01

The magnitude of shear stress sustained by Cercom WC increases with an increase in shock-induced stress. For example, at shock stress of 82 GPa, the value of sustained shear strength is 6 GPa.

Shear Strength of WC from Lateral Stress Measurements

Four experiments were performed to measure shear strength of WC to a maximum impact stress of magnitude 13 GPa. The results of these experiments are given in Table 2. The lateral stress profiles recorded in these experiments are shown in Figure 5. These profiles were recorded at 2 mm from the impact surface in WC targets. These profiles in WC show a two-step structure similar to ones observed in AD995. But the second steps continue to ramp up and do not become steady within the recording time. The ramp is most pronounced in the experiment conducted at 13 GPa in WC. The net effect of the ramp is that the value of shear strength calculated from the lateral stress profile is time dependent and the final value of shear strength remains indeterminate.

Figure 6 displays a plot of shear strength versus impact stress of WC. In this figure the values of shear stresses (strength) calculated from the Hugoniot and equation of state of WC is represented by "Hydrodynamic". The values of shear strength calculated from linear elastic theory with the assumption that the Poisson's ratio remains unchanged with pressure are represented by "Elastic theory". The values of shear strength for ARL and SNL experiments were calculated from the measured shock Hugoniot of WC and the equation of state of WC. Just as in the case of AD995, the values of shear strength designated as "Elastic theory" and "Hydrodynamic" are indistinguishable from one another for impact stresses

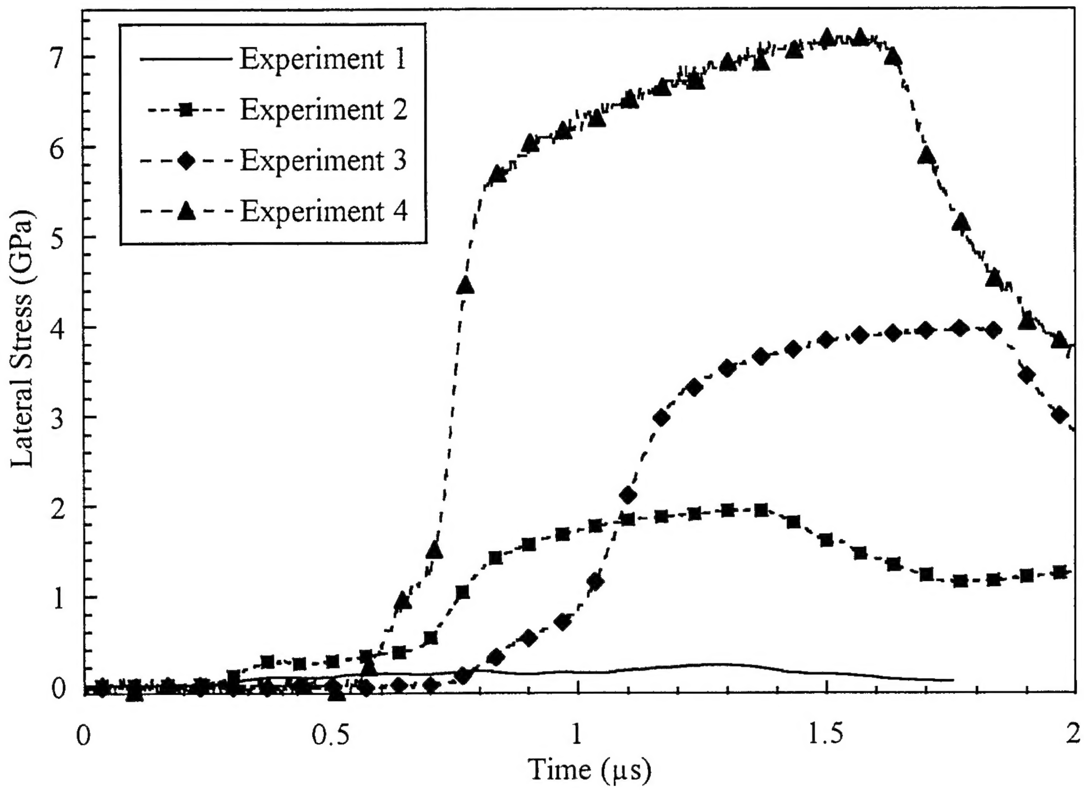

Figure 5. Lateral stress profiles in WC.

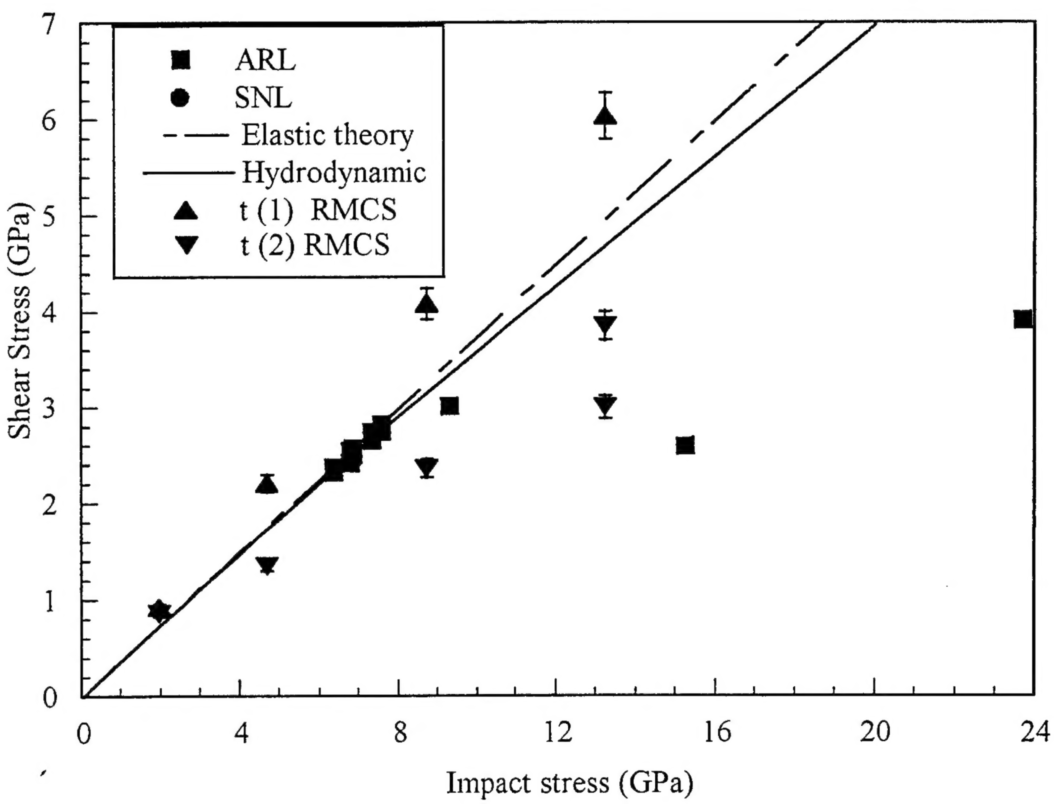

Figure 6. Shear stress versus impact stress in WC

equal to or less than the HEL of WC i.e., 7 GPa. Again, just as in the case of AD995, $\tau(1)$ lies considerably above the "Elastic theory" locus once the impact stress exceeds 1.95 GPa. $\tau(2)$ at this impact stress equals in magnitude to $\tau(1)$. All the remaining values of $\tau(2)$ corresponding to the impact stress above 1.95 GPa, lie below the both "Elastic theory" and "Hydrodynamic" locus, suggesting that shear strength of WC at 2mm away from the impact surface is considerably reduced even when shocked below its HEL. The values of $\tau(2)$ at impact stresses 8.7 and 13.2 GPa are within the scatter of estimated values of shear strength obtained from the previous work [2]. However, it is not clear from these experiments whether the values of $\tau(2)$ at these impact stresses have reached a final magnitude due to the interruption of continued observed ramp in the lateral stress profiles due to arrival of release wave from the free surface of the WC target in these experiments. Finally, the lateral stress wave profiles indicate that WC may be undergoing inelastic deformation above 1.95 GPa, i.e., at an impact stress much below its HEL of 6.6 GPa.

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